Modeling the emergence of COVID-19: a systems approach

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***Abstract*—In December 2019, a novel coronavirus disease (COVID-19) suddenly emerged in Wuhan, China. In March 2020, WHO declares the coronavirus outbreak a pandemic. The virus has spread quickly to all over China and most of the countries and regions within the increasing urbanization and globalization, infected more than three million people worldwide. A crucial factor that may significantly affect the spread of COVID-19 is the multiple, interactive, emergent, and complex characteristics and systems of the social systems. This paper describes a systems approach modeling and analyzing the emergence and spread of COVID-19 in urban systems, seeking to combine the multi-layer urban structure between complex infrastructure systems, human activities and policy systems. Moreover, a complex network model is built to illustrate the diffusion of the virus with or without the intervention of policy systems under the different policy intensity by the changed basic reproduction number (R_0). Besides, a system dynamics model, including feedback loops and changes, is proposed to demonstrate how the COVID-19 spreads out under the interactive and interrelated characteristics and systems of the complex systems at different levels.**

Keywords*—Systems approach, Complex Systems, Policy Intervention, Scale-up and spread, System dynamics, Novel Coronavirus, COVID-19

I. Introduction

A. *The origin, development and transmission of the novel coronavirus disease*

A novel coronavirus (COVID-19) has emerged recently caused by an acute respiratory syndrome and led to a large outbreak from Wuhan to the whole China in January 2020. Meanwhile, human-to-human coronavirus transmission has been confirmed on January 20, while the virus had spread widely with limited predictability [1]. Direct person-to-person transmission may occur when people are in close contact, such as talking to each other, eating together and staying in one vehicle with confined space [2]. A fact should be highlighted that the outbreak happened about ten days after the Chinese New Year travel rush, where millions of Chinese travel long distances through the public transportation system and reunion with other family members and relatives. The travel rush infers a large number of people get cross-infected during their travel and gathering since the incubation period has been proved to be 1 to 19 days [1]. Wuhan, as the epicenter of COVID-19 in China, is the seventh-largest city in China with more than 11 million permanent residents, and it owns sizeable urban systems with extensive and interlaced transportation network. As the transportation hub and most densely populated city in central China, Wuhan plays a crucial role in the Spring Festival travel rush [3]. The pandemic virus spreads through complex and massive transportation infrastructure system, where every system and characteristic of the social systems play a unique role in the outbreak. These systems interact with each other at a particular time and spatial dimension to accelerate or inhibit the spread and development of the epidemic. Therefore, the COVID-19 may not only be analyzed from a pharmacologic and epidemiology section but also be concerned with the complexity and interaction of the dynamic social structure, infrastructure, information flow, policy implementation and human behavior, etc. In addition, the nontrivial and complicated interactions among the systems create the uncertainty and emergent results [4] and finally result in a large-scale spread of COVID-19 in the complex urban systems.

B. *The characteristics and systems of the complex systems under the attack of COVID-19*

The complex urban systems, including broad and numerous systems, influence human behavior, wellbeing, health, transportation, information flow, policymaking as well as the spread of COVID-19. The multi-sectoral and multi-layered systems are complex, primarily because of the interaction, interconnection, feedback, self-organization, emergence among the systems [3]. These interactive systems, in turn, shape complex systems and even produce unpredictable outcomes. Within the complex and interactive urban systems, the virus can replicate and spread to the cities unconsciously at the early stage, even to the world under the developing urbanization and globalization. From the spatial perspective, viruses can spread in homes, buildings, communities and eventually to the whole city. In terms of time, viruses can transmit through scale-free networks, leading to an exponential increase in the number of infected people without or with little intervention at the early stage.

In this decentralized situation, people move spontaneously and interact with infrastructure systems such as transportation and logistics system, information system and other public systems. Individuals, as the occupant, user and component of the social systems, affect and shape each system by interacting and self-organizing behavior in the urban structure. Factors at multiple levels, including infrastructure, human behavior, macro-social to micro-social policymaking, have the implications for the development or the restriction of the COVID-19. Moreover, the development of the urban immune system for COVID-19 is inconsistent with the complexity of the infrastructure systems. Massive and high-density human flow in large cities such as Wuhan overwhelms the capacity of the urban immune system. Triggered by the interaction and evolution between the elements and systems related to COVID-19 in the social systems, the seemingly stable but complex urban systems eventually break down, resulting in the collapse of the urban immune system and the outbreak during the Chinese New Year from Wuhan to all over the world.

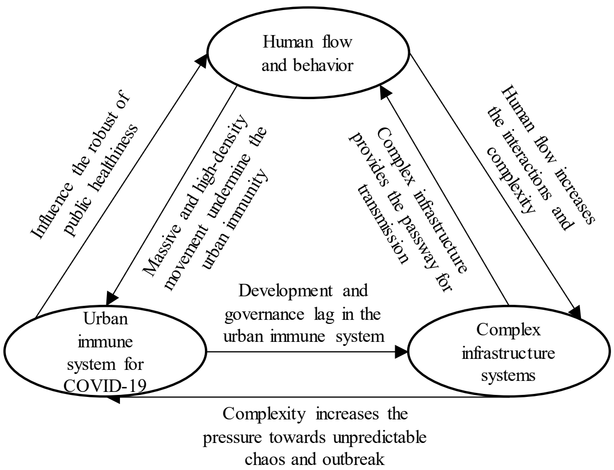

Fig. 1. Feedback loops between human flow and behaviors, urban infrastructure systems and immune system

Figure 1 shows the feedback loops between human flow and behavior, urban infrastructure systems and immune system to explain how the COVID-19 spreads in the urban systems, in turn, affect the systems of systems. The constant spread of COVID-19 is the emergent property of complex systems of systems, which is the result of the interaction and feedback of various characteristics and cannot be simply understood as the combined of the individual components [5]. Namely, this outbreak is a typical event of complex systems in which systems interact with each other and with the external environment, leading to the pandemic.

II. The Affection of Human-Urban Structure on COVID-19 in the Complex Social Systems

To better understand how the urban systems linked to the COVID-19, the complex systems are analyzed from different perspectives and levels [6]. A simple social structure shown in Figure 2 with multilayers is proposed to explain how interconnection in complex infrastructure systems, human flow, individual behavior, policymaking and society units will affect or be affected by infectious diseases from the perspectives of the interaction, complexity, and feedback. Each layer of the structure has interaction and interconnection with other systems and environments. As the virus evolving from the bottom-up in social systems, a series of top-down policies have been introduced to curb the development of the virus from macro-scale(country, region, urban) to micro-scale(community, single building). On the other hand, the feedback from the bottom will, in turn, be summarized up to affect policymaking. At this particular time, the entire society has become stakeholders in the unprecedented events and is fully engaged in what was happening during the crisis, in which every system and characteristic of urban systems play a role at different stages to affect the epidemic's spread.

A. Complex infrastructure systems

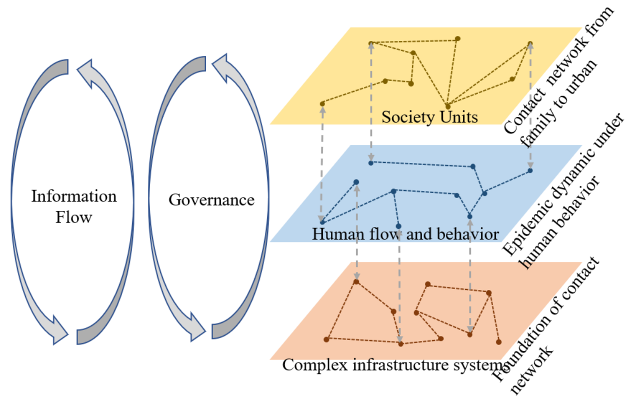

Fig. 2. A simple multi-layer complex urban structure

The complex infrastructure systems, not only limited to the physical infrastructure (e.g., transportation system, energy system) but also included information system (IS), Internet of things (IoT), 5G, cloud computing, artificial intelligence (AI) in cyberspace [7], [8], allow information to be collected, processed and transmitted efficiently. For example, in isolated areas in Wuhan, doctors can communicate with patients remotely through 5G technology and analyze the collected diagnosis data timely by AI technology. The practical AI technology developed by Alibaba DAMO Academy can review a computerized tomography (CT) image to assist the diagnosis of the infection of the novel coronavirus instead of waiting for the test kits. Moreover, contact-tracing and susceptible case-finding become more manageable once the patients' moving histories have been collected and reported to the cloud-based database confidentially and anonymously. When the database grows and becomes sufficient in terms of analysis purposes, it will flow the information back to the policymakers or interest parties for further consulting and policymaking to support the crisis response initiatives. By using the cyber technologies, the policymakers can adjust its policy based on the result of the virus spreading speed and procedure promptly; the patients' previous movements can be tracked to alert others who had close contact with them immediately; the hospital can make rational treatment plans with the support of AI and 5G remotely; local governments and community administrations can create different policies based on the feedback data, etc.

The above examples indicate that the infrastructure systems in cyberspace interact with human behavior, information flow and policymaking to affect the spreading speed and the diagnosis process of COVID-19. Moreover, the cyber-physical system is involved as the interaction of all the characteristics developed its complex network together. The physical infrastructure systems are critical concerning the spread of the virus with highly developed and interactive transportation and logistics networks. The first stage of the outbreak in China coincidentally overlays with the period of the Chinese Spring Festival, which results in high pressure on the transportation system. The interaction between human flow and physical infrastructure (i.e., airplane, train, bus) immensely increases the chance of person-to-person transmission followed spatially contagious diffusion (SCD) [6]. Population movements increase the chance of exogenous infections by the contacts between person and person as well as between person and environment, especially within vehicles and indoor places that have confined space. The geographical distribution of the virus expands through the human flow and cause more infections through time. Besides, the self-organization character of human behavior has been enhanced within the complex infrastructure network, which links to the emergence of COVID-19 in complex systems.

B. Human flow and behavior

Human flow and behavior are the second layer of the complex urban systems, which interact with complex infrastructure systems, policymaking systems and society units. The human behavior with self-organization, non-linearity and dynamic characters increases the complexity of the urban systems. Understanding self-organizing processes enables the development of intervention designs that can be successful in a variety of contexts by providing feedback regarding the implementation of multiple policies [9], [10]. Individuals' behavior in urban systems highly affects the diverse and dense infrastructure systems, which, in turn, increases the complexity of human behavior.

Moreover, the information flow about the COVID-19 throughout the whole urban systems partly determines the individual behavior, suggesting that when individuals are exposed to a lot of crowdsourcing information during the outbreak, they may exchange views and change their behavior to different aspects. On the other side, feedback mechanisms of information flow can be formed based on the changes in human behavior, supporting necessities for the policymaking and other stakeholders. Individuals, whose behavior has been severely affected by the novel coronavirus, perceive the risk and then help to formulate patterns of interaction among the healthcare system, information system, social network, policymaking, and other systems.

In the meantime, some targeted policies will emerge consequently. The policies would affect the public assessment of perceived risk and behavior, especially in the prevalence of epidemic [11], which will cause a systemic change for contact networks. And changes in contact networks can have a significant impact on infrastructure systems, which, in turn, can influence the rate and scale of outbreaks. Therefore, every evolution of the social sub-systems and characteristics have the interconnectedness and interdependency, which will further affect the spread of the virus. Interdependency is the structures and processes through interaction, information exchange and decision making among poeple in the complex social network [12]. The degree of interdependency or interrelatedness among each system and characteristic impacts human behavior and human flow, thus affecting the conduction and uptake of an intervention.

C. Society units

Society units can be explained as the place where individuals live and where policy is implementing from the spatial dimension. Society units can be a single-family house, a community comprised of buildings and blocks, or the whole city in the complex systems. In society unit level, the virus spreads from a person to family at the beginning and then spread out to the community at the early stage, which is a bottom-up pattern. While policy adoption is a top-down pattern, communities receive and convey the policies from the authorities to families and persons within the community in Wuhan and some of the other cities based on the epidemic situation.

A series of management policies, aiming at different society units by the authorities, have been conducted in Wuhan and other cities in Hubei province as responding to the spread of the epidemic in the early stage. On January 23, 2020, the central government issued a policy informing that all the public transport operations, including buses, flights, ferry, coach, railways, subways and highways, should be suspended, and all the transport hub would be shutdown. People in Wuhan city are not allowed to leave the city without special permission from the authorities. This incident usually is called "Wuhan lockdown" to quarantine the epicenter of the Wuhan COVID-19 outbreaks from the urban level. Subsequently, a series of public policies have been introduced from different spatial levels but may vary for different cities and regions.

For instance, from the single-family level, the policy of house-to-house searches and inquiries has been implemented to inhibit the spread of the virus in Hubei province. From the community level, some of the communities adopt closed management policy, and people who don't live in this area are forbidden to enter into the community to prevent exogenous infections. From the district level, travel restriction policy has been implemented to minimize the population mobility. After the central government sets the policy direction from the top, different districts and communities within different society units can specify various policies from the dimension of time, spatiality and intensity for their urban systems according to the needs of epidemic prevention. Each society unit implements its own strategy with the premise of following the central government policy. The interaction within the systems of human behavior, human psychological factors, information flow and infrastructure formulates a complex and integral feedback mechanism, pushing the government policy continued to be improved.

III. The Complex Network of the Spread of COVID-19 Under the Intervention Policies

To illustrate the difference in the transmission of COVID-19 with or without policy intervention in different temporal-spatial dimensions, a complex model is established in this paper. R_0, known as the basic reproduction number, is recognized as a critical parameter of an infectious disease in both the theoretical

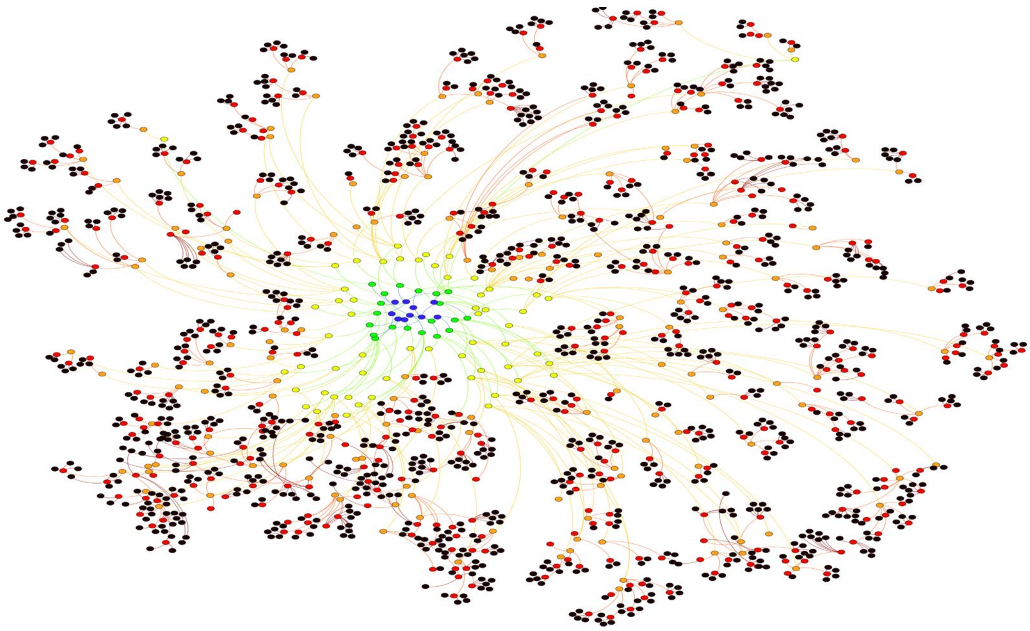

Fig. 3. The spread of COVID-19 within the complex network (iterations color are blue, green, yellow, orange, red and black, sequentially)

studies and the practice to control the transmission, as it indicates the number of secondary cases can be produced by a certain infectious person [13]. From the policy implementation perspective, as a significant indicator of the transmissibility of infectious disease, R_0 has its mathematical meaning: $R_0 > 1$ indicates the disease may start to spread and lead to an outbreak, where the artificial intervention policies should be implemented to control the spread of infectious diseases; $R_0 < 1$ indicates the disease is under control by some of the effective policy, such as quarantine and isolation in Wuhan [5], [11].

The Poisson distribution is used to model the frequency of transmission with a group of individuals under the assumption that all the infected individuals have the same infectiousness in the complex network and will spread the virus to others before isolation, and all the susceptible individuals do not have antibodies in the early stage of transmission. The number of secondary infections that are caused by each infectious individual is a random number under the Poisson distribution with mean R_0 in the initial stage [5]. Here, R_0 is obtained from the paper written by Joseph T. Wu et al. [1] who applied the data of infectious individuals from December 1, 2019, to January 25, 2020, recorded in Wuhan to infer R_0 and the outbreak size. In the baseline scenario, the estimated R_0 for COVID-19 is 2.68 (95% CrI 2.47–2.86). The total infected number can be formulated by Formulas (1) and (2).

$$N = \sum_{i=0}^{n} N_i \tag{1}$$

$$N_{i+1} = \sum_{j=1}^{N_i} k_{ij}, \text{ where } k_{ij} \sim Poisson(R_0),\ N_0 = 10 \tag{2}$$

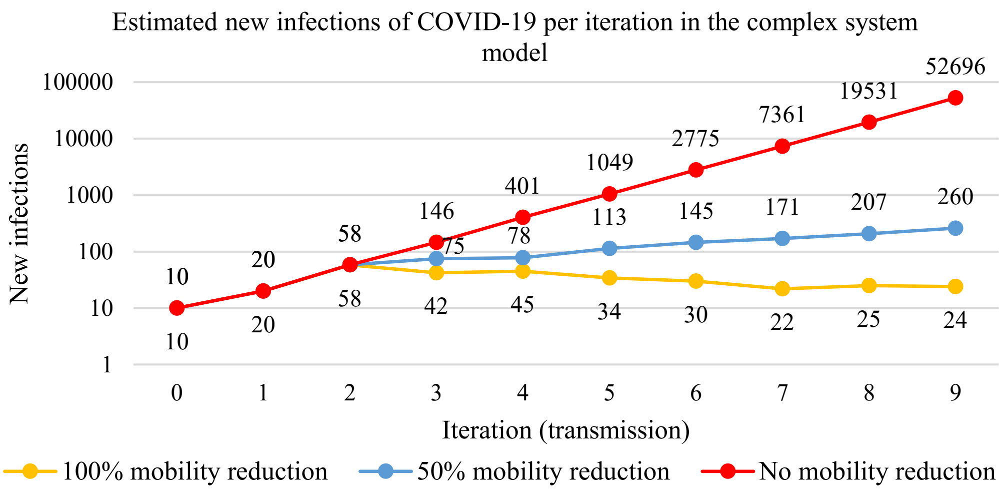

Fig. 4. Increased infections per iteration in the complex system network with different intervention policies

Where the initially infected individuals in the simulation are set as N_0 = 10. N_i is the number of infected cases at the i^{th} transmission (Figure 4 shows 9 times transmission) and N is the summation of N_i, which is the total number of infected individuals. k_{ij} is the number of individuals infected by individual j at the i^{th} to $(i+1)^{th}$ transmission. The propagation tendency shown in Figure 3 illustrates the speed of transmission for COVID-19 without any intervention in the early stage. A random experiment shows that after five times of transmissions, the infectious numbers rapidly increase to 1049 and after nine iterations, the infectious number increase to 52696, which is out of control shown in Figure 4.

A series of policies have been conducted and promoted for COVID-19 by the policymakers and other stakeholders to inhibit the rapid increase. The adoption of policies with different intensities and types may affect individuals from physical and psychological perspectives and trigger social dynamics. Policies issued for ordinary citizens in Wuhan included but not limited to delay the resumption of school, postpone businesses reopen after the spring festival holiday, popularize the knowledge about the virus, require the use of face masks in public areas, quarantine at home voluntarily, and wash hands frequently [11]. These policies can be summarized as reducing mobility, minimizing interpersonal contact rate and paying enough attention to self-protection outside.

According to the estimation in the paper of Joseph T. Wu et al. [1]. R_0 can be reduced to 1.30 by the reduction of 50% mobility. In this simulation, considering the policies take a certain time to be formulated after the emergence of COVID-19 while people in society units require some time to implement the policies, the mobility will decrease after a certain time. Based on the reasonable assumption, after two iterations of virus spread, R_0 will drop from 2.68 to 1.30, implying that the virus gradually became relatively controllable by the adoption of a serious of policies. Comparatively speaking, if up to 100% mobility can be deducted, that is most of the citizens stay at home voluntarily, after two times transmission R_0 will be decreased to less than 1 (set 0.9 in the model), implying the number of increasing infections will become less and less, and the virus will become totally under control. The comparisons shown in Figure 4 indicate that the effect of policy execution is closely related to the time and intensity of policy release. Therefore, timely policy formulation and risk communication play a significant role in suppressing the spread of the virus. In the meantime, the policy delay should be considered during the process of formulation and implementation.

IV. Deepening the Assessment: Illuminating Dynamic, Causal, Reinforcing and Balancing Relationships

A system dynamics approach empowers a more comprehensive and dynamic causal understanding by highlighting the interdependencies, interactions, and interrelationships of the characteristics and systems of the complex systems. This section provides a cause-effect model called the causal loop diagram (CLD) [14] that may demonstrate the spread of COVID-19 by multiple feedback loops in the complex systems shown in Figure 5. A "+" or "-" symbol represents the positive or negative relationship for the causal link related to the spread of COVID-19.

The largest reinforcing loop R1, including all the outermost factors, is that after the adoption of the voluntary self-quarantine policy, which can be widely publicity and effectively enhanced by the guidance of effective crowdsourcing information flow. The daily mobility will decrease while the conduct of working from home and shutdown non-essential business. Thereafter, the density of public transportation will reduce accordingly. Since the low density of public transportation lowers the person-to-person contact, the chance of secondary infectious will also be reduced after a certain incubation period. With a smaller number of newly detected and confirmed infections, fear among the population may be eased. However, when people are in panic, their ability to identify valid and accurate information may be weakened due to some of the psychological factors. Verifying the accuracy of the information and suppress the propagation of harmful rumors are critical for decision making and policy implementation in disaster response. Therefore, reducing people's fear in order to improve the risk communication and enhance the accuracy and timeliness of information

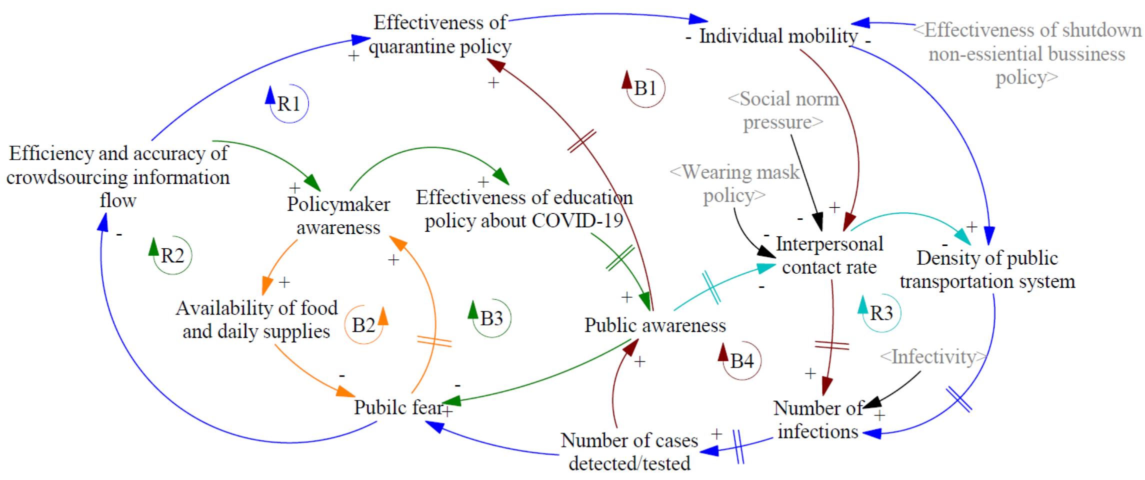

Fig. 5. Causal loop diagram with feedback loops related to COVID-19 in complex system. R is reinforcing loop while B reprsents balancing loop

dissemination can play a positive role in the implementation of policies such as self-quarantine policy.

Another reinforcing loop R2 refers to the policymaker's awareness of the severity of the COVID-19, urging adoption of education policy about COVID-19 to strengthen public awareness to prevent cross-infection gradually. Moreover, when people have sufficient knowledge about the virus, they tend to be fearless by an enhanced sense of self-protection. Furthermore, screened crowdsourcing information will be lead to the correct direction and will be continuously discussed, assisting policymakers in terms of awareness and decision making in the end. Besides, in reinforcing loop R3, when the public is aware of the severity of the COVID-19, people tend to reduce contact or maintain a safe physical distance with others, especially care about not congregating together in one place. Thus the number of secondary infections may be reduced gradually.

The balancing loop B1 is to demonstrate the importance of public awareness related to the policy system. The lower public awareness will cause less effectiveness of the multiple policy application, indicating a trend of not significantly decreasing individual mobility that leads to an increase in the number of infections due to the high exposure rate. The increase in the number of infections, however, will build up public awareness, oppositely turning the loop in B1. Even without the recommended self-quarantine policy, the enhanced public awareness may decrease individual mobility to avoid contact and decrease infection rates, shown as balancing loop B4. On the one hand, as shown in balancing loop B2, when the concern among the population caused by the virus in certain areas over time discovered by the policymaker, the resources such as food and daily supplies will be mobilized to the designate area to balance the market supply in terms of reducing fear. That will, in turn, affect the intensity and types of policies. On the other hand, the balance between public awareness and policy intensity can also be found in balancing loop B3, emphasizing the significance of continuously maintaining a high policy intensity on the adoption of education policy so that individuals will stay alert at the early stage of the outbreak.

V. Conclusion

This paper advocates that the rapid spread of COVID-19 can be regarded as the emergent result of the interaction, self-organization and interconnection in the characteristics and systems of the systems. The spread and outbreak of COVID-19 in urban-level can be thought from the multilayer and interconnected systems consisting of multiple infrastructure systems (transportation system, logistic system, and cyber-physical system), various human activities (human flow, human behavior) and multiple policymaking systems (community, city, region, nation). A complex network model is proposed to demonstrate the spread of COVID-19 with or without policy intervention, as well as the effectiveness of policy with different intensity and timing. Moreover, a system dynamics model related to the spread and inhibition of COVID-19 adds a level of big-picture thinking about the policymaking, human behavior change, infrastructure systems and contact rate ensuring that the major feedback mechanisms with reinforcing and balancing loops are accounted. Future work may consider modeling the interaction and interconnection of human behavior and the spread of the virus in complex systems with various policies.

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